A Three-Phase Transformer

RELATED APPLICATION

This application is a Continuation In Part of Serial Nos. PCT/IL99/00562 filed October 5, 1999 and PCT/IL00/00243 filed April 27, 2000.

FIELD OF THE INVENTION

This invention relates to a three-phase electrical transformer and a method for manufacturing thereof.

BACKGROUND OF THE INVENTION

A transformer is a known electrical device widely used for transferring energy of an alternating current in the primary winding to that in one or more secondary windings. It typically contains two or more electrical circuits comprising primary and secondary windings, each made of a multi-turn coil of electrical conductors with one or more magnetic cores coupling the coils by transferring a magnetic flux therebetween.

Presently known three-phase transformers usually utilize E+I magnetic cores in a flat structure. Such a transformer includes several interconnected magnetic cores located in one plane. U.S. Patents Nos. 4,893,400 and 5,398,402 disclose transformers having a magnetic core made of an amorphous metal strip wound into a core over a mandrel, with one leg of the resulting core being subsequently cut off and with forming the metal into a rectangular shape. This transformer is manufactured in the following manner. A piece of rectangular steel is wrapped around the outer periphery of the amorphous metal core. The amorphous metal is then annealed, and the core is encapsulated in a resinous coating, except the cut leg. This allows the opening of the cut leg. The layers of amorphous alloy strips of the two edges are oriented so that the edges define top and bottom surfaces, each surface having a discontinuity defining a distributed gap portion extending from the top surface to the bottom surface. The coils are placed over two long legs and the cut leg is closed. The joint is then sealed.

I hereby certify that this paper is being deposited with the United States Postal Service as EXPRESS MAIL in an envelope addressed to: Assistant Commissioner for Patents, Washington, D.C. 20231, on April 26, 2001
Express Label No.: EL846165365 US
Signature: B. [signature]

According to US '400, the sealing is made with glass cloth and an ultraviolet-curable resin to provide the structure by the "fit and cure" method. This method is costly and labor-intensive. The transformers having amorphous metal cores manufactured according to this method cannot be repaired without causing damage to the core.

According to US '402, the sealing is made with a porous material such as woven cotton cloth or paper. The porous material is folded over the joint and secured into position. An additional piece of porous material is placed through the window of the core, wrapped around the core and secured there. Electrical grade steel is disposed around the transformer core and is closed around the core joint and tack-welded. This structure allows the cut leg to be opened to permit replacement of a defective coil. The operation, however, is time-consuming and labor-intensive.

US Patent No. 5,441,783 discloses a technique of the kind specified, wherein a coating used to impregnate the core joint is a porous material with a viscosity greater than about 100,000cps and a bonding material with a viscosity of at least about 100,000cps. The porous material comprises strands of fiber, and the bonding material is thixotropic epoxy. Although the coated cores have good magnetic properties, their manufacture requires costly and complex operational steps. Moreover, the method of repairing these cores is labor-intensive.

Another common disadvantage of the transformers manufactured according to the techniques disclosed in the above patents is that annealed amorphous metals become extremely brittle, and thus break under mechanical stress, for example, during the stage of closing the core joint.

In the transformers of the above kind, a planar core structure is used. US Patent No. 4,639,705 discloses a transformer structure of another kind, having a spatial magnetic core system. This structure has advantages over the planar "E+1" structure, such as the reduced quantity of required magnetic materials (by about 20-30%), reduced volume of the transformer, reduced core losses (by about 20-30%), and balanced currents in the three phases of the primary windings. However, to manufacture a transformer in accordance with the technique disclosed

in US '705, complex production technology as well as a complex repair technology, are required.

US Patent No. 4,639,705 discloses a transformer structure of another kind, having a spatial magnetic core system. This structure has advantages over the planar "E+1" structure, such as the reduced quantity of required magnetic materials (by about 20-30%), reduced volume of the transformer, reduced core losses (by about 20-30%), and balanced currents in the three phases of the primary windings. However, to manufacture a transformer in accordance with the technique disclosed in US '705, complex production technology as well as a complex repair technology, are required.

However, the commercially available amorphous ribbons (strips) are typically limited in width (up to 200mm). Thus, the width of the strip is typically much smaller than that required for the height of a transformer core.

It is known from the disclosure in US Patent No. 2,909,742 that in order to obtain a desired height of the transformer core, a number of toroids can be stacked on top of each other. This technique, however, suffers from energy losses caused by unavoidable introduction of unwanted air gaps between each two adjacent toroids.

US Patent No. 1,164,288 discloses a technique of fabricating a cylindrical magnetic core for a power transformer. The magnetic core is made from coiled strips, wherein the core is of greater axial dimension than the width of the strip. To manufacture the core, a plurality of layers of the magnetic steel strips is simultaneously coiled to form the cylindrical core. The sum of the width of the strips in each layer is equal to the axial dimension of the core, and at least one longitudinal edge of each strip is staggered is relation to those in adjacent turns of the resultant coil.

SUMMARY OF THE INVENTION

It is accordingly a need in the art to facilitate the manufacture and maintenance of a three-phase transformer, by providing a novel electrical transformer structure and a method of its manufacturing.

It is a major feature of the present invention to provide such a transformer that has higher efficiency and smaller magnetic core, and that uses lower quantities of materials per unit electrical power and/or has better maintainability, as compared to those of the conventional transformers of this kind.

A three-phase transformer according to the invention has a spatial symmetrical structure of a magnetic circuit. The magnetic circuit comprises two spaced-apart parallel plate-like elements, and three spaced-apart parallel column-like elementary circuits, which are substantially perpendicular to the plates and are enclosed therebetween forming a mutually symmetrical structure.

According to one aspect of the present invention, there is provided a method for manufacturing a three-phase transformer, the method comprising the steps of:

(i) producing two substantially plate-like elements of a magnetic circuit of the transformer in the form of toroids by winding at least one magnetic strip;

(ii) producing each of three column-like elementary circuits of said magnetic circuit in the form of toroid of a multi-layer structure by winding predetermined number *N of* packages of magnetic strips about a central axis of the toroid, each package being composed of a predetermined number *n* of layers formed by *n* strips placed on top of each other;

(iii) forming each of the columns with a radial slot filled with an insulating material;

(iv) mounting a coil block on each of the columns obtained in step (iii) to form the corresponding one of the three phases of the transformer;

(v) mounting the coil blocks carrying columns between the plate-like elements in a spaced-apart parallel relationship of the column-like toroids, such as to form a spatial symmetrical structure about a central axis of the transformer, spacers between the elements of the magnetic circuit of the transformer being filled with a material containing a magnetic powder.

According to another aspect of the invention, there is provided a three-phase transformer manufactured by the above method.

In general, for the purposes of the present invention amorphous strips or silicon steel strips (ribbons) can be used. The multi-layer structure of the column-like toroids provides for avoiding a problem associated with that ribbons available in the market may be limited in the width, for example, the width of an amorphous ribbon is typically less than the desired height of the transformer core. Such a multi-layer structure is composed of the predetermined number *N* of ribbon packages (stacks) aligned along the central axis of the toroid. Each package is composed of the predetermined number *n* of ribbons placed one on top of the other (i.e., aligned along an axis perpendicular to the central axis of the toroid) and shifted one with respect to the other a certain distance. Hence, each layer in the structure is composed of *N* strips (ribbons) arranged along the central axis, wherein air gaps naturally exist between each two adjacent strips of the layer. The layers are shifted with respect to each other such that each of the air gaps in one layer is overlapped by *(n-1)* strips of the other layers.

It should be understood that, since the heights (lengths) of plate-like and column-like toroids are different, the number of packages therein may be different. Generally, the plate-like toroid may be manufactured from a single strip, provided its width satisfies the height of the plate-like toroid. The provision of such packages is associated with the need to form the toroid of a desired height from several magnetic strips, caused by the limited width of the strip, and the unavoidable existence of air gaps between each two adjacent strips. If both, the plate-like and column-like toroids are made of strips packages, the packages are identical (i.e., comprises the same number of strip layers), while the number of packages is different for the flat and vertical toroids.

When manufacturing the transformer core from amorphous strips, the following steps should also be done:

- annealing each of the plate-like toroids in a magnetic field directed perpendicular to a central axis of the toroid, and carrying out impregnation of each of the annealed plate-like toroids; and
- prior to performing step (iii), annealing each of the three columns in a magnetic field directed along a central axis of the column, and carrying out impregnation of each of the column-like toroids.

Each of the column-like elementary circuits (toroids) may be formed of several axially mounted toroidal elements, each having a radial slot filled with an insulating material.

The elementary circuits are spaced from each other and from the plate-like elements by insulating spacers. All the spacers may be formed of plastic with filler of a magnetic powder with the concentration of 20-50%.

According to yet another aspect of the present invention, there is provided a three-phase transformer comprising a magnetic circuit formed of amorphous strips and three coil blocks, wherein the magnetic circuit comprises:

- two spaced-apart, parallel, plate-like elements in the form of toroids; and
- three spaced-apart, parallel column-like elementary circuits in the form of toroids, each column-like elementary circuit carrying the corresponding one of said three coil blocks and serving for the corresponding one of the three phases, wherein the column-like elementary circuits are substantially perpendicular to the plate-like elements and are enclosed therebetween such as to form a spatial symmetrical structure about a central axis of the transformer;

wherein

- at least the column-like toroids are in the form of identical multi-layer structures, each structure being composed of an array of N amorphous strip packages wound about the central axis of the toroid and aligned along said central axis, each package being a stack of n layers formed by n amorphous strips aligned along an axis perpendicular to said central axis and shifted with respect to each other a predetermined distance along said central axis such

that each of the air gaps naturally existing between each two adjacent strips in the layer is overlapped by *(n-1)* strips aligned along the axis perpendicular to the central axis of the toroid; and

- each of the column-like toroids is formed with a radial slot filled with an insulating material.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to understand the invention and to see how it may be carried out in practice, a preferred embodiment will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in which:

Figs. 1 and 2 illustrate schematically exploded and assembled views of a three-phase transformer structure according to the invention;

Fig. 3 is a section taken along lines A-A in Fig. 2;

Figs. 4 and 5 illustrate more specifically some constructional parts of the three-phase transformer of Figs. 1-2, showing two possible examples, respectively, of assembling means for assembling the transformer;

Fig. 6 more specifically illustrates the structure of the elementary magnetic circuit of the transformer of Figs. 1-2, utilizing a plurality of toroids;

Figs. 7 and 8 illustrate two stages in a method of assembling the structure of the elementary magnetic circuit of the transformer of Figs. 1-2;

Figs. 9A to 9D illustrate the principles of a ribbon package based technique of winding a transformer core suitable to be used in the three-phase transformer according to the invention; and

Fig. 10 schematically illustrates the main components of an apparatus for manufacturing the transformer core composed of ribbon packages.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

Referring to Figs. 1 and 2, the main components of a three-phase transformer **10** constructed according to the present invention are illustrated. The transformer **10** comprises a magnetic circuit **12** formed by an upper plate-like

element **14**, a lower plate-like element **16**, and three parallel identical column-like elementary circuits, generally at **18**. The magnetic circuit **12** is arranged such that the plates **14** and **16** are parallel to each other, and the columns **18** serve as supports between the plates, thereby forming a cage-like structure spatially symmetrical about a central axis **CA**. In the present example, each of the plates **14** and **16** is a toroid, and is made of amorphous ribbons **22** wound about a central hole **23** to form the planar toroid. Further provided are three coil blocks **20**, each for mounting on a corresponding one of the columns **18**. As shown in Fig. 2, each of the coil blocks **20** includes a primary winding **20a** and a secondary winding **20b**. Thus, each phase of the transformer **10** is formed by the column-like elementary circuit **18** with the corresponding coil block **20** mounted thereon.

The transformer **10** has a modular structure, namely, the plates **14** and **16**, and the columns **18** can be easily assembled together and disassembled, as will be described more specifically further below. When one of the plates **14** or **16** is removed, the coil blocks **20** can be removed as well, thereby enabling, for example, to repair the coil.

In the present example, each of the plates **14** and **16** has a generally triangular shape with rounded sides and corners. After forming the plate **14** of the desired shape and size, an excess-ribbon portion **22a** is cut off. The amorphous ribbon **22** is made of an alloy having soft ferromagnetic properties, as required for the magnetic circuit of a transformer. Amorphous ribbon is known to have good ferromagnetic properties. The structure of the transformer **10** according to the invention allows for beneficial use of these properties in a practical transformer structure.

Each of the columns **18** is also a toroid. In the present example, each of the toroids **18** is formed of three toroidal element **18a, 18b** and **18c** stacked on top of each other. This construction enables to achieve a desired height of the column **18**, notwithstanding the fact that the width of amorphous ribbon is typically limited. The desired height of the column-like elementary circuit **18** can be achieved by

winding the toroid **18** from a predetermined number of layers, each formed by a plurality of magnetic strips, as will be described more specifically further below. Thus, the present invention allows for producing a transformer with any desired height of the column-like elementary circuit **18**.

As shown in Fig. 2, the entire structure is held together with three de-mountable bands **24** (only two of them being seen in the figure), each having a screw (or spider) **26** to tighten the band. Structural members **28** are provided, each located between the corresponding one of the bands **24** and each of the plates **14** and **16**. A base **30** supports the entire structure. An inner, upper surface **16a** of the plate **16** is brought into contact with lower surfaces of the columns **18** to transfer magnetic fluxes therebetween, as will be described more specifically further below.

Fig. 3 illustrates a section taken along line **A-A** of Fig. 2, showing more specifically the lower plate **16** and the three columns **18** of the magnetic circuit **12**. Each column **18** is formed with a central hole **32**, and the columns **18** are arranged symmetrically about the central axis **CA**. As shown, the structural member **28** is located between the corresponding one of the bands **24** and the plate **16**. The plate **16** preferably has a protective coating **34** aimed at prolonging its life.

Turning back to Figs. 1 and 2, the operation of the transformer **10** consists of the following. As a current passes through each primary winding **20a** of the coil block **20**, a magnetic flux is generated and propagates along the corresponding column **18** between the upper and lower plates **14** and **16**. Arrows **36, 38** and **40** show fluxes generated in the three columns **18**, respectively. The magnetic flux flowing through the column **18** generates an induced voltage in the secondary winding **20b** of the corresponding coil block **20**. The device having this structure thus functions as a three-phase transformer.

Thus, the electric current, for example, with the working frequency of 50Hz, is supplied from a power source (not shown) to a terminal of coil of the primary winding **20a**, and, whilst passing through the coil turns, creates the basic magnetic flux **36**. Let us now consider the moment of passing of the magnetic flux along one phase of the transformer. Assuming, for example, that at a given moment the flux

36 flows up. Then, the flux **36** is divided into two identical fluxes **42** and **44** in the plate **14**. These fluxes **42** and **44** flow along two identical portions of the toroidal plate **14**, and, then, flow down through the two other cores **18**. The flux **42** changes into flux **38**, and the flux **44** changes into the flux **40** passing down through the columns **18**. Then, the fluxes **38** and **40** flow along two equal paths of the toroidal plate **16**. Whilst passing along the toroidal plate **16**, the flux **38** changes into a flux **46**, and the flux **40** changes into a flux **48**. The fluxes **46** and **48** are transferred into the column **18** forming the sum flux **36**, which flows up. Thus, the magnetic flux loop is closed. The fluxes of the other phases of the transformer flow in the similar way summing up the total magnetic flux.

As indicated above, the plates **14** and **16** could have a circular shape. In this case, the flux streams **42, 44, 46** and **48** will flow along circular paths therein. In the example of Figs. 1 and 2, each of the plates **14** and **16** is shaped like an equilateral triangle with rounded sides and corners. This results in a shorter path for the flux streams in the plates **14** and **16** between the columns **18**, i.e., the shape of the flux streams is closer to a straight line. This enables to achieve a lower magnetic reluctance, or better conductance of the magnetic flux. To manufacture each of the plate-like elements **14** and **16**, the amorphous ribbon **22** is secured to a mandrel made of a non-magnetic material and having a triangular cross section, which is then rotated about its axis. When the desired size of the plate **16** is achieved, the plate is fixed in that state using either impregnation or welding procedure, and the excess of ribbon **22a** is cut off. Due to the triangular cross-section of the mandrel, the plate **16** has a generally equilateral triangle shape with rounded corners and sides.

Each winding in the coil block **20** is made of a copper wire. Each coil may have a winding and a case insulation compatible with the working voltage and cooling system used. If air-cooling is used, a relatively thick insulation may be required. In case the transformer is immersed in oil, a thinner insulation may be used for the same voltage. Oil may be used for cooling as well as for insulation between the windings.

The cross-sectional area of the column **18** and the corresponding area on the plates **14** and **16** are defined by the ferromagnetic property of the amorphous alloy these parts are made of, and by the transformer working voltage. The height of each column **18** and the distance between the columns is derived from the dimensions of the coil blocks **20**, according to the cross-sectional area of the wires, the number of turns and the required insulation. The dimensions of the plates **14** and **16** are such as to form a base for the whole cross-sectional area of all the columns **18**, when the columns **18** are located at the required distance therebetween. This allows the passage of the magnetic flux from the columns **18** to the plates **14** and **16**.

In the present example, each of the toroids **14, 16, 18a, 18b** and **18c** is made of amorphous ribbon of about 20mm in width and 25μm in thickness. It should, however, be noted that the toroids **18a, 18b** and **18c** may be made from ribbons in the range of 10-100mm wide, or as allowed by the ribbon manufacturing process.

Fig. 4 more specifically illustrates the column **18** of the magnetic core **12** of the transformer and means for assembling the transformer. The column **18** is mounted between the upper and lower plates **14** and **16**. The primary and secondary winding **20a** and **20b** of the coil block **20** are mounted on the column **18**. The structure is held together with the de-mountable bands **24** which are tightened with the screws **26**. The structural member **28** is located between the band **24** and each of the plates **14** and **16**. The de-mountable bands **24**, screws **26** and structural members **28** constitute together the assembling means. It should be noted that the type and size of the assembling means could depend on the dimensions and rated power of the transformer.

As the inner (upper) surface **16a** of the plate **16** comes in contact with a lower surface **50** of the columns **18** to transfer the magnetic fluxes in the transformer, a narrow air gap **52** may be created therebetween. The width of the gap **52** may, for example, be about 0.2mm. This gap **52** should preferably be filled with a magnetic paste, to improve the overall ferromagnetic property of the magnetic loop, namely to decrease the magnetic resistance. The magnetic paste may include an amorphous powder with soft ferromagnetic properties, having

particle size larger than 20μm, and a binding insulating material like transformer oil or epoxy resin. The concentration of the amorphous powder in the paste is usually between 50% and 90%. Any other suitable means can be used to minimize the gap **52** and its influence on the magnetic loop. An outer (lower) surface **16b** of the plate **16** may be formed with a protective coating.

Similarly, a narrow air gap **54** may be created between a surface **14a** of the element **14** and an upper surface **51** of the column **18**. The gap **54** should also be filled with a magnetic paste. An outer (upper) surface **14b** of the plate **14** should preferably also be formed with a protective coating.

Fig. 5 illustrates one of the columns **18** of the magnetic circuit **12** associated with a somewhat different assembling means, as compared to that of the example of Fig. 4. To facilitate understanding, the same reference numbers are used for identifying those components, which are identical in the examples of Figs. 4 and 5. Here, the upper and lower plates **14** and **16** and the column **18**, are held together by a threaded beam or screw **56**. The structural members **28** that are attached to each of the plates **14** and **16** include means adapted for the thread and nut structure.

It is important to note that, when manufacturing transformers of various power, one comes into conflict caused by the absence of strips made of amorphous materials with arbitrary width, and by the need for a magnetic circuit element having the height much larger than the strip's width. Reference is made to Fig. 6, more specifically illustrating the structure of the column-like elementary circuit **18**. In the present example, the column **18** is formed by the three toroids **18a, 18b** and **18c**. It should, however, be understood that the column **18** could be in the form of a single toroid. All the toroids **18a, 18b** and **18c** (or the single toroid) are formed with the central hole **32**. An outer cover **50a** of the toroid is preferably made of an insulating material, for example, a glass-cloth laminate impregnated with an epoxy resin. The toroids **18a, 18b** and **18c** are made of amorphous ribbon, and have a radial slot **70** to decrease losses and to prevent high voltages from being induced into the windings of the toroids. Such a high voltage may cause breakdown of the insulation between the adjacent layers of the toroid. The radial slot **70** may, for

example, be of 1mm in width, or of any other appropriate width for a specific transformer design. The slot **70** may be made with a corundum disk (not shown) of 200mm diameter and 0.5-1mm thickness, using a cooling liquid and the toroid secured in a suitable fixture. The slot **70** is filled with an insulating material, for example a glass-cloth-base laminate. In the present example, cylinders **74** made of an insulating material are inserted into the hole **32**, so as to align together the toroids **18a-18b** and **18b-18c**. The cylinders **74** may have a central hole, to allow the insertion of a threaded beam (not shown).

One of the parameters characterizing the operation of a transformer is the idle current. This value depends on the characteristics of the magnetic materials used and the values of the air gaps **52** and **54** (Fig. 4) between the separate parts of the magnetic circuit. The affect of the air gap can be reduced in the following manner:

The air gaps **52** and **54** are filled with a magnetic paste or with a spacer made of plastic having a filler of magneto-conductive powders, for example, amorphous iron-based powders. The thickness of such a spacer may, for example, be 0.1-0.2mm. The induction in the air gap is reduced, which can be achieved by increasing the cross sectional area of the air gap, through which the magnetic flux passes, by several times.

To achieve better mechanical strength, the lateral surface of the column is coated with a glass-cloth-base laminate band impregnated with epoxy resin that is wound about the column. After coating, the band is sintered at the temperature of about 100-130°C. To provide sufficiently good magnetic properties and allow for fitting the elements close to each other (when assembling the column), the upper and lower surfaces of the column may be milled and polished to within 0.1mm, with the total length of the column being set to within a 0.1mm tolerance. To prevent stratification of the column during the machining process, it is necessary to chuck the operated zone in a special fixture.

Figs. 7 and 8 illustrate the main principles of assembling the transformer **10**. Fig. 7 shows the structure of the column **18** after mounting the first coil of the coil

block **20** (i.e., the secondary winding **20b**) thereon. Spacers **80** made of an insulating material are used to mechanically attach the winding **20b** to the column **18**, while keeping the parts electrically insulated from each other. Terminals **82** of the winding **20b** are exposed to allow electrical connections thereto. During the formation of the structure, a specific distance $\mathbf{d_1}$ is kept between the lower end of the winding **20b** and the lower end of the column **18**. The structure is symmetrical, having the same distance $\mathbf{d_1}$ at the upper end of the winding **20b**.

Fig. 8 shows the transformer **10** with both primary and secondary windings **20a** and **20b** of the coil block **20** mounted thereon. The primary winding **20a** is secured to the secondary winding **20b** by spacers **84**. The spacers **80** and **84** are made of an insulating material. Terminals **82** and **86** are used to connect the secondary and primary winding **20b** and **20a**, respectively, to a power source and load (not shown).

Thus, the entire assembling procedure is performed in the following manner. The coil of the secondary winding **20b** is mounted on the column **18** and secured thereon with the spacers **80**. Then, the coil of the primary winding **20a** is mounted on that of the secondary winding **20b** and secured thereon with spacers **82**, the coil **20a** being located in such a manner as to keep a predefined distance $\mathbf{d_2}$ from each of the ends of the column **18**. The coils of the other two phases are mounted on the corresponding columns **18** in a similar manner.

Turning back to Fig. 2, the plate **16** is set in a horizontal position with the working surface **16a** pointing upwards. This working surface is the planar surface of the toroid **16** that was previously cleaned from the excess of the impregnating material and, optionally, polished.

Thereafter, a layer of the magnetic paste, having the thickness about 0.2mm, is deposited on the plate **16** in the areas where the columns **18** are to be mounted. The three columns **18** with coil blocks thereon are mounted on the plate **16** symmetrically about the central axis **CA**. Then, another layer of the magnetic paste, having the thickness about 0.2mm, is deposited onto the upper surfaces of the

columns **18**, and the upper plate **14** is mounted on the three columns **18** to complete the structure.

As described above, the elements **14**, **16** and **18** of the magnetic circuit **12** are secured to each other using three de-mountable bands **24** with the screws **26** to tighten each band. The structural members **28** made of an insulating material are located between the bands **24** and the plates **14** and **16**. The screws **26** are rotated so as to tighten the bands, thus securing the transformer parts together. Rotating the screws **26** in the opposite direction can easily dismantle the transformer. The bands **24** become loose and allow the removal of the columns **18** and the plates **14** and **16**. Each coil can be then removed from its column, if desired.

The above technique allows for multiple cycles of dismantling/assembling the transformer, without causing any damage to the constructional parts of the transformer. This may facilitate the repair of the transformer, and may save work and materials needed therefor.

Various parts of the transformer may be separately and concurrently produced, and then assembled together in the final step. The entire method of manufacturing the transformer consists of the following.

Initially, the amorphous ribbons **22** are produced from an alloy having soft ferromagnetic properties, as will be described more specifically further below. Then, the elements (e.g., toroids) **14**, **16**, **18** of the magnetic circuit **12** are produced. Each column-like elementary circuit **18** may comprise one or several toroids, according to the required height of the column **18** and the width of each toroid. In the case that the column **18** includes several toroids, each of the columns is assembled from these toroids. The coil block **20** is assembled (in the above-described manner), each including the primary and secondary windings **20a** and **20b**. Alternatively, each winding may be separately produced and assembled as a separate unit. Each of the fixed column-like toroids is then formed with a radial slot, which is filled with an insulating material. Then, the impregnation and/or coating of the elements and/or windings are carried out. To assemble the transformer from the so-produced elements, the columns **18** are inserted into the

corresponding coil blocks **20**, the coils are secured in place, the columns **18** are mounted at the corners of the plate **16**, and the plate **14** is mounted on the columns **18**. All the constructional parts **14**, **16** and **18** are secured together using screws, tension bands or similar mechanical means.

The preparation of the amorphous ribbon toroids will now be described. At present, to obtain sufficiently good magnetic properties, the as-cast amorphous ribbons are annealed at a temperature of about 350-550°C. The disadvantage of this known method is that the amorphous ribbons become extremely brittle after annealing, usually breaking under mechanical stress or during winding of a toroid. To overcome this deficiency when manufacturing a transformer core (toroidal like magnetic circuit) from the amorphous ribbons, the present invention utilizes the following preparation scheme:

An as-cast amorphous alloy ribbon is coated with an insulating layer. The thickness of the two-sided insulation needs to be no more than about 5μm. It should, however, be noted that for a low-voltage transformer, this stage may be omitted;

Then, a toroid (like the toroids **14**, **16**, **18**) is wound from the as-cast ribbon. Since the magnetic circuit is composed of two "flat" toroids **14** and **16**, and three vertical magnetic cores **18** configured like toroids, when the required height of the toroid exceeds the width of an amorphous ribbon available in the market, the toroid is to be wound by packages of ribbons. When the required height *L* of a toroid is equal to the width of the available amorphous ribbon, the conventional winding procedure can be used, namely, spiral-like winding of a toroid.

A mandrel made of a non-magnetic material is typically used for winding a magnetic core. Generally, the mandrel may be in the form of a triangular flat element with rounded edges, or in the form of a tube. However, when dealing with a high power transformer, the tube-like mandrel is preferably used, and for winding of vertical toroids **18** the mandrel has to be a tube. The height of the tube-mandrel is equal to that of the obtained toroid, and the diameter of the tube-like mandrel depends on the dimensions of the transformer and is determined by electrical

calculations. When staring the winding process, the end of an amorphous ribbon is fixed to the tube by an insulating material, and when finishing the winding, the remaining end of the ribbon is fixed to the last winding of the toroid in a similar manner.

When manufacturing high-power transformers, the height of each of toroids **14**, **16** and **18** typically exceeds the width of the commercially available amorphous ribbon. Therefore, in this case, the winding procedure should be carried out by means of ribbon packages. Such a package is composed of *n* ribbons placed one on top of the other, such that an upper ribbon is shifted (displaced) with respect to the underneath ribbon along the ribbon's width. Such a displacement is usually in the range 1-8mm, and is determined in accordance with technological parameters of the transformer and with acceptable induction in the ribbon, namely, from the ratio between the values of saturation and working induction.

The need for such ribbon packaging is associated with the fact that, when placing one amorphous ribbon adjacent to the other (along the central axis of the toroid), an air gap (typically of about 0.5-2mm) is formed between the two adjacent ribbons. The ribbon packages based winding is thus used to enable the passage of a magnetic flux (which propagates vertically in the toroid **18** and partly in toroids **14** and **16**) from a first ribbon to the second neighboring one spaced from the first ribbon by the air gap.

As the selected value of working induction may, for example, be $B_w=1.35T$ at the maximal induction value (saturation) of $B_{sat}=1.55T$, then the induction reserve in each ribbon can reach 0.2T. Therefore, when forming a toroid from the packages of ribbons, where adjacent ribbons aligned along the central axis of the toroid are spaced from each other by an air gap, the magnetic flux would pass over this air gap, thereby passing from ribbon to ribbon. In this case, the magnetic flux in each ribbon should not exceed the induction value of $B_{sat}=1.55T$, and, therefore, *n* parallel ribbons should be located in the zone of the air gap, wherein $n \geq B_w/(B_{sat}-B_w)$. In the present example of the above values of B_w and B_{sat}, the number *n* of ribbons in the package should be not less than 7. In other words, for

the amorphous ribbons available in the market, the number n of ribbons in the package is selected to be equal to 7. The toroid is thus wound by the 7-ribbon package.

Since the height (length) of the toroid is significantly higher than the ribbon's width, then N packages should be aligned along the height of the toroid, wherein $N=L/b$. Here, L is the height of the toroid and b is the width of the ribbon. It should be noted that each of the "flat" toroids **14** and **16'**, as well as each of the vertical toroids **18**, is wound by identical ribbon packages, i.e., with the same number n of ribbons in the package (7 ribbons in the present example), while the number N of packages (aligned along the height of the toroid) is different for the flat and vertical toroids.

The principles of such ribbon package based winding technique will now be described with reference to Figs. 9A-9D. As shown in Fig. 9A, a tube-like mandrel **116** (of the length slightly exceeding the desired length of the toroid) is fixed in a winding machine (not shown) for rotation about the central axis **114** of the mandrel. In the present example, the mandrel has an outer diameter of 30mm, a wall thickness of 2mm, and the height of (L+20mm), wherein L is the height of the toroid. A disc **117** is placed at one end of the mandrel (right end **116A** in the present example), in order to prevent the "creeping" of the ribbons along the axis of the mandrel. The surface of the mandrel **116** at the end **116A** has a conic shape, and the first package S_1 of ribbons (containing n ribbons - seven ribbons L_1-L_7 in the present example) is fixed at this end, for example, by gluing. From this end of the mandrel, all along its length, N packages of ribbons (not shown) are aligned. As a result, an n-layer structure is obtained with the length slightly exceeding the length of the toroid. The outer diameter of the toroid (**14, 16** and **18**) is determined from the electrical calculation.

The revolution of the mandrel until the diameter of the toroid reaches the required value, results in a multi-layer structure shown in Fig. 9B, wherein $\mathbf{D_{out}}$ is the outer diameter of the toroid, and **L** is the calculated length thereof. Thereafter, two sections are made across the toroid along lines C-C and M-M (Fig. 9B),

thereby cutting off conical portions and obtaining a calculated toroid **110** of Fig. 9C having the multi-layer structure **112** shown in Fig. 9D.

Thus, the transformer core **110** is in the form of a cylindrically shaped toroid of the desired (calculated) height **L**. The toroid **110** is formed by winding the multi-layer structure **112** of magnetic strips (ribbons) about the central axis **114** of the mandrel **116** (constituting a central axis of the toroid). The multi-layer structure **112** is composed of *N* packages (five such packages S_1-S_5 being shown in the example of Fig. 9C) aligned along the length (axis) of the toroid, each package being a stack of *n* parallel layers of *n* amorphous ribbons (seven ribbons L_1-L_7 in the present example as shown in Fig. 9D), which are arranged along an axis perpendicular to the central axis **114** (i.e., along the radius of the toroid). This arrangement results in that the air gaps **118A-118G** (formed between each two adjacent ribbons and being typically about 0.5-2mm) are aligned along the length of the toroid (along the axis **114**). By shifting the *n* ribbons (7 in the present example) in the package with respect to each other in a direction along the width of the strip is such that each of the air gaps is overlapped by (n-1) strips of the other layers (6 strips in the present example). It should be understood that the number of ribbons in the package, which defines the thickness of the winding, is defined by the required power of the transformer.

The transformer having the magnetic circuit **12** (Fig. 1) in the form of two flat toroids **14** and **16** and three vertical toroids **18**, each having the structure **112**, operates in the following manner. Magnetic fluxes **46** and **48** enter the magnetic circuit **12**, and are combined into the common magnetic flux **36**. Such a magnetic flux enters the butt-end of the toroid **18** (having the structure **112** of Fig. 9D), and is divided into separate concentric fluxes passing through each ribbon layer L_1-L_7, such that each unit of flux **F** (Fig. 9D) passes from package to package within the zone of the air gap. For example, the magnetic flux **F** while passing in the ribbon layer L_1 reaches the air gap **118A** and passes into the parallel ribbons L_2-L_7 of the same package. Having passed through these ribbons a distance up to the next air gap in the path of the flux **F** (i.e., the air gap **118A** of the second package S_2), the

flux **F** returns to the ribbon layer L_1 of the first package S_1, where it propagates along the axis **114** up to the next air gap **118A.** Here, the flux turns to again pass the entire package S_1 along the axis perpendicular to the central axis **114.** By this, the magnetic flux passes the entire length of the toroid 18 (Fig. 1) and enters the upper flat toroid 14.

It should be noted that, if the toroid **18** is formed of several toroidal elements, then to force the layers of the toroidal elements to be laid exactly on top each other, the mandrel may have cheeks or delimiters mounted thereon. Using this scheme, the variation in toroid's width may be limited to a small value, for example about ±0.2mm.

When the transformer core (toroid) is manufactured as described above, the last layer of the toroid is secured to the adjacent layer to prevent the toroid from folding. This may be achieved, for example, by using resistance welding.

Thereafter, the complete toroid is annealed at a temperature of about 350-550°C, preferably in a furnace with controlled atmosphere, for a desired time period defined by the type of metal. The toroid may be annealed with the mandrel still inserted therein. Annealing may be performed with or without the application of an external magnetic field (longitudinal or transverse) to the toroid.

Then, the toroid is impregnated with an organic binding material, for example, an epoxy resin in a vacuum chamber or in an ultrasonic bath. After the impregnation, the toroid is placed in temperature-controlled environment. The impregnation may be performed with the mandrel still in the toroid.

The mandrel is removed from the toroid. The excess of an impregnation material is removed from the planar surfaces of the toroid, or at least the surface of one of the elements **14** and **16.** The working surfaces (areas used to transfer the magnetic flux) may be polished to obtain planar surfaces for good flux transfer and low magnetic resistance. The ends of the toroid may be made parallel to within 0.2mm. It should be noted, that the polishing procedure can be performed prior to the step of annealing, while the toroid already has a fixed shape, and the amorphous ribbon is not yet brittle and is thus more workable.

As described above with reference to Fig. 6, the radial slot **70** is cut in the toroid **18**. The Slot **70** may be made with a corundum disk (not shown) of a 200mm diameter and 0.5-1mm thickness, for example, by using a cooling liquid and with the toroid secured in a suitable fixture. The slot **70** is preferably filled with an insulating material, for example, a glass-cloth-base laminate.

To achieve better mechanical strength, the lateral circular area of the toroid is coated with a glass-cloth-base laminate band that is wound about the toroid. After the coating procedure, the band is sintered at the temperature of about 100-130°C.

It should be noted that the above-described ribbon package based technique is suitable for manufacturing the transformer core from amorphous ribbons limited to those available in the marker (i.e., having insufficient width for covering the entire height of the core). Generally, all the magnetic circuits in the transformer could be manufactured from silicone steel, in which case the ribbon package based winding technique may not be used. Although the use of silicon steel ribbons leads to the increased losses in the magnetic circuit, it enables to simplify the technological process, owing to the fact that a strip of the required width can be selected for manufacturing the toroid. Therefore, the above construction utilizing silicone steel can be used in the applications having reduced requirements to the effectiveness of the transformer.

The technological process of the manufacture of the magnetic circuit from silicone steel consists of the following:

- The toroidal plate (**14** and **16**) is wound from the strip produced from silicone steel having, for example, the width of 0.3mm and an insulating coating of 3-10μm thickness. In this case, the coefficient of the winding density lies in the range of 0.8-0.96. The width of the strip corresponds to the height of the toroidal plate.

- After the winding procedure, the plate is impregnated by an insulating varnish, e.g., vacuum or ultrasound impregnation. The varnish solidifies at the temperature of 80-105°C.

- A bandage made of a glass-strip is wound along the perimeter of the plate, and then impregnated by epoxide varnish with further thermo-treatment at the temperature of 80-105°C.

- The working surface of the plate is treated, e.g., milled, for obtaining a plane with the unevenness value not exceeding 10μm.

- The column like elementary circuits **18** can be manufactured similar to the toroidal plates **14** and **16**. When using the toroid manufacturing technology, the width of the strip is selected to be larger than the height of the column on the allowance value of mechanical treatment, e.g., 2mm. The mechanical treatment of both butt-ends of the column **18**, in distinction to that of the plate **14** and **16**, is performed with the unevenness value not exceeding 10μm and the unparallelism of the butt-ends not exceeding 20μm. Moreover, the longitudinal slot **70** (e.g., of 1mm in thickness) is made, and a plate (not shown) made of an insulating material, for example glass-textolite (resin-dipped fabric laminate), is inserted into the slot **70**. A bandage made of a glass-strip is wound on the outer surface of the column, and then impregnated by epoxide varnish with further thermo-treatment at the temperature of 80-105°C.

Following are the calculation results corresponding to the transformer of 400kVA power made of amorphous ribbons and having the above design of assembling the separate parts of the magnetic circuit **12** to each other:

- the cross sectional area of the column-like elementary circuit, S_{core}=293cm^2;
- the surface area of the projections having the height of 6mm in at the butt-end of the column, S^1=469cm^2;
- the butt-end surface area of the projections, S^2=150cm^2;
- the total area on the projections, along which the magnetic flux passes, S_Σ=619cm^2.

In this case, for magnetic induction, we have:

$$B_{\delta} = \frac{B_m \cdot S_{core}}{S_{\Sigma}}$$

wherein B_m is the induction in the column. When B_m=1.3(T), B_{δ}=(1.3x293)/619=0.61(T), which results in the reduction of idle current by two. When selecting the depth of the recess equal to 12mm, the idle current reduces by 4.

Mathematical analysis of a three phase transformer made according to the present invention was performed, and results were compared to those for a conventional transformer having an "E+1" magnetic circuit structure. The evaluation relates to the three-phase transformer having rated power values of 10kVA, 25kVA, 100kVA and 630kVA. The analysis includes computation of the core and winding electrical losses and weight. All calculations were performed for a fixed, predefined value of overall efficiency. Calculation results are presented below in Tables 1 to 5.

In all the examples presented in the tables 1-5, the working frequency f is 50Hz. Following are the variables in the tables 1-5:

- P_w, wherein W is the winding loss;
- magnetic circuit loss P_{Fe} (W);
- winding weight G_w (kg);
- magnetic circuit weight G_{Fe} (kg);
- total transformer weight G_{tr} (kg);
- efficiency η (%);
- transformer height B_{tr} (mm);
- transformer length L_{tr} (mm);
- transformer width B_{tr} (mm);
- transformer volume V_{tr} (m^3);
- output power P_2 (kVA);
- primary voltage U_1 (V);

- secondary voltage U_2 (V)

Table 1

P_2=10kVA; U_2=220V; U_1=380V

Parameters	*Type of transformer*	
	AMT, dry – Israel	TSZM-10/0.4
Core design	Toroid	E+1 type
Core material	Amorphous metal	Silicon steel
P_w (W)	330	256
P_{Fe} (W)	12	78
G_W (KG)	26	59
G_{Fe} (kG)	58	40
G_{tr} (KG)	8 5	99
η (%)	96.7	96.7
H_{tr} (mm)	214	465
L_{tr} (mm)	349	600
B_{tr} (mm)	349	335
V_{tr} (m^3)	0.026	0.093

Table 2

P_2=25kVA; U_2=220V; U_1=380V

Parameters	*Type of transformer*	
	AMT, dry – Israel	TSZM-25/0.4
Core design	Toroid	E+1 type
Core material	Amorphous metal	Silicon steel
P_w (W)	697	558
P_{Fe} (W)	19.3	157
G_W (KG)	64.5	133
G_{Fe} (kG)	95.5	77
G_{tr} (KG)	160	200
η (%)	97.2	97.2
H_{tr} (mm)	242	555
L_{tr} (mm)	441	706
B_{tr} (mm)	441	463
V_{tr} (m^3)	0.047	0.18

Table 3

P_2=100kVA; U_2=380V; U_1=22.5kV

Parameters	*Type of transformer*	
	AMT dry - Israel	Siblok, dry
Core design	Toroid	E+1 type
Core material	Amorphous metal	Silicon steel

P_w (W)	2024	1700
P_{Fe} (W)	48	440
G_W (KG)	132	160
G_{Fe} (kG)	238	405
G_{tr} (KG)	371	565
η (%)	97.9	97.9
H_{tr} (mm)	706	1180
L_{tr} (mm)	1270	1300
B_{tr} (mm)	1270	925
V_{tr} (m^3)	1.13	1.41

Table 4

P_2=630kVA; U_2=380V; U_1=22.5kV

Parameters	***Type of transformer***	
	AMT dry - Israel	Siblok, dry
Core design	Toroid	E+1 type
Core material	Amorphous metal	Silicon steel
P_w (W)	7071	5600
P_{Fe} (W)	136	1600
G_W (KG)	650	570
G_{Fe} (kG)	683	1740
G_{tr} (KG)	1333	2310
η (%)	98.87	98.87
H_{tr} (mm)	866	1850
L_{tr} (mm)	766	1820
B_{tr} (mm)	766	1186
V_{tr} (m^3)	0.51	4.05

Table 5

P_2=630kVA; U_2=380V; U_1=22.5kV

Parameters	***Type of transformer***	
	AMT, dry - Israel	Allied Signal, Oil, USA
Core design	Toroid	E+1 type
Core material	Amorphous metal	Amorphous metal
P_w (W)	5880	5835
P_{Fe} (W)	148	186
G_W (KG)	537	487
G_{Fe} (kG)	739	932
G_{tr} (KG)	1276	1419
η (%)	99.05	99.05
Oil	-	+
Tank	-	+

The computations for the transformers having various power ratings and voltage levels indicate the advantageous features of the transformer constructed according to the present invention, including among others the following features:

- decrease of total weight by about 14% to 43%;
- decrease in cost by about 3% - 22%;
- decrease in transformer volume by about 20% to 87%.

An experimental transformer manufactured according to the present invention has the following parameters:

P_2= 1kVA; U_1= 380V; U_2= 220V; f= 50Hz; η =92.66%; G_{tr}= 16.4kg

It was found that this transformer has good maintainability, and the above-described modular structure thereof enables its easy dismantling and reassembling, while the conventional transformer of the kind specified has the following characteristics: η=91% and G_{tr}=20kg. It is thus evident that the structure according to the invention enables to achieve the 18% decrease in the transformer weight at higher efficiency.

Fig. 10 illustrates the main components of an apparatus **120** for manufacturing the transformer core **110**. The apparatus **120** comprises seven bobbins **B$_1$-B$_7$** (generally, *n* bobbins), each for carrying *N* strips of a corresponding ribbon layer to be fed to the mandrel **116**. The strips are previously wound onto the bobbins in a manner, which will be described further below, and simultaneously fed onto the mandrel **116**, by a suitable driving assembly, which is not specifically shown.

The driving assembly may be of any known suitable kind, and may be associated with the mandrel **116** for driving the revolution thereof, while the bobbins are rotatably mounted on their shafts (not shown) to rotate against the tension of the feeding layers. In order to provide the desired tension of the layers during the coiling procedure, the driving assembly may also be associated with the shafts of bobbins for driving the revolution thereof. The construction may be such that the bobbins are driven together for rotation about the mandrel, which, in this case, is mounted stationary.

Further provided in the apparatus **120** is a guiding assembly **122**, comprising one or more guiding rollers, generally at **124**, and a pair of width limiting rollers **126** accommodated at opposite ends of the mandrel **116** extending normally to the direction of movement of the layers onto the mandrel.

As further shown in the figure, the layers are prepared on the bobbins with the corresponding shift between the strips of each two adjacent layers as described above. To this end, either the corresponding arrangements of strips of different layers are previously determined, and the strips are wound on the bobbins accordingly, or identically wound bobbins are prepared and then cut by any suitable cutting tool.

It should be noted, although not specifically shown, that the layers of sufficient width, appropriately shifted with respect to each other, could be wound on the mandrel, and the so produced core then cut at opposite ends. In this case, the bobbing and/or guiding means may be appropriately shifted.

Those skilled in the art will readily appreciate that various modifications and changes can be applied to the preferred embodiments of the invention as hereinbefore exemplified without departing from its scope defined in and by the appended claims.